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EFFECTS OF SHOCK IMPINGEMENT AND OTHER FACTORS ON LEADING-EDGE HEAT TRANSFER

by Dennis M. Bushnell

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EFFECTS OF SHOCK IMPINGEMENT AND OTHER FACTORS ON LEADING-EDGE HEAT TRANSFER*

By Dennis M. Bushnell
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SUMMARY

An investigation was conducted at a Mach number of 8 to determine the effects on stagnation-line heat transfer of shock impingement, chordwise grooves in the leading edge, and end contamination of the leading-edge boundary layer from an adjoining surface.

The shock-impingement tests were conducted with an unswept cylinder. A flat plate inclined at an angle of 12° to the flow was used as the shock generator. The cylinder was separated from the shock generator to eliminate the effects of flow separation in the root region. A local peak in heating that was about twice the undisturbed heating level was observed in the stagnation region of the cylinder where a vortex sheet impinged on the leading edge. The vortex sheet originated at the intersection of the plate and cylinder shocks. Comparison of these data with previous measurements on similar configurations indicates that the magnitude of the peak in heating depends on the proximity of the shock impingement to the tip or root region in which the attached leading-edge boundary layer first develops. On the basis of this comparison and additional tests in which the shock impingement occurred closer to the tip of the cylinder, it is concluded that for leading edges at small sweep angles, shock impingement occurring far from the root of the leading edge causes only moderate increases in heating. If impingement occurs near the root of the leading edge, factors of the order of up to 10 times the undisturbed heating level are possible. Previous investigations have already shown that shock impingement on a leading edge which is at a large sweep angle causes no local increase in heating.

Heat-transfer measurements were made along the leading edge of a 76° swept fin mounted on a flat plate. Tests were made with and without a series of small chordwise grooves cut into the leading edge to simulate construction details. Analysis of the observed heating distribution on the leading edge with the grooves indicates that some fraction of the stagnation-line boundary layer is bled off by the grooves, so that a new viscous sublayer grows downstream of each groove. The general level of heating was about the same as or less than the leading-edge heating data obtained on the same configurations without the grooves.

The present heat-transfer data from the smooth 76° swept fin indicated that transition of the leading-edge boundary layer occurred at a Reynolds number,

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based on free-stream conditions and leading-edge diameter, of approximately 2×10^5. A survey of heat-transfer data for swept leading edges indicates that for leading edges having adjoining surfaces such as the flat plate in the present investigation, a transition Reynolds number of 2×10^5 is generally applicable for Mach numbers from 2 to 8 and sweep angles greater than 40°. On the other hand, the transition Reynolds number for leading-edge configurations without adjoining surfaces was generally found to be greater than 8×10^5.

INTRODUCTION

The flow in the vicinity of leading edges is often complicated by the presence of phenomena associated either with adjoining surfaces or with departures from smooth-leading-edge geometry which are necessitated by structural considerations.

The present investigation is a study of the effects on leading-edge heat transfer of three types of these "interfering" flow fields. These interfering flows, depicted in figure 1, are leading-edge shock impingement, the effect of chordwise (normal to leading edge) grooves, and end contamination of the leading-edge boundary layer from an adjoining surface.

Several investigations of the leading-edge shock-impingement problem have been previously conducted (refs. 1 to 10), and for highly swept leading edges, it has been shown that no local increases in heating occur at shock impingement and that the leading-edge heat transfer can be predicted by using local conditions in simple theories.

The available data for leading edges at small sweep angles (refs. 4 to 10) indicate that a local peak in leading-edge heating occurs in the vicinity of shock impingement. Measurements of the magnitude of this peak have indicated factors from about 2 to 10 times the undisturbed level. These peaks have been generally measured in the region of the impingement of a vortex sheet which emanates from the vicinity of the intersection of the impinging shock and the leading-edge bow shock as shown in figure 2. This apparent discrepancy of a factor of 5 in the available data may in some cases be due to an insufficient density of instrumentation such that the exact local peak was not observed. Also, some of the available data are for situations in which shock impingement occurred in the vicinity of a separated-flow region near the root of the leading edge and the effects of the separated-flow reattachment and shock impingement could not be separated. The purpose of the present investigation was to obtain the effect of shock impingement on stagnation-line heat transfer for an unswept cylinder without these sources of uncertainty. A temperature-sensitive-paint technique was used to provide the magnitude and location of any local peaks in heating with greater accuracy than conventional thermocouple models. Also, the cylinder was separated from the shock generator so that the effects of flow separation in the juncture region could be eliminated and data could be obtained for a situation analogous to that of shock impingement occurring far out on a leading edge as well as close to the tip. Shock impingement occurring far out on the leading edge is generally of greater practical interest.

Typical delta-wing configurations may have small chordwise grooves in the leading edge. (These grooves would be present because of the lapped, sliding joints used in the fabrication of the leading edge to allow for thermal expansion.) Previous investigations have been conducted to determine the effect of grooves on leading-edge heat transfer (refs. 11 and 12), but either the number of grooves was not sufficient or the Reynolds number range was not large enough to allow application of these results to current problems of interest. Therefore, an investigation was conducted to determine the effect of a large number of small chordwise grooves on the leading-edge heat transfer of a 76° swept fin over a Reynolds number range sufficient to provide both laminar and turbulent stagnation-line boundary-layer flow for a similar leading edge without the grooves.

As shown in reference 13 for low speeds, the effect of the flow over a surface adjoining a leading edge is to cause premature transition of the entire leading-edge boundary layer. To ascertain if an adjoining surface can cause premature transition for hypersonic flow and for large sweep angles, a smooth 76° swept leading-edge fin mounted on a flat plate was tested, and the transition Reynolds number was compared with previous transition data for similar configurations (fin-plate or cylinder-plate models) and "undisturbed" or "delta wing" configurations without any adjoining surface.

SYMBOLS

D	leading-edge diameter
h	heat-transfer coefficient
k	thermal conductivity
M	Mach number
N_{Nu}	Nusselt number, hD/k_{∞}
p	pressure
R	Reynolds number
x	distance along leading edge (fig. 8)
α	angle of attack
Δ	distance along leading edge from effective root to vortex-sheet impingement
Λ	sweep angle

Subscripts:

∞	free stream
D	leading-edge diameter
1,2	regions of flow (fig. 2)
max	maximum
transition	boundary-layer transition

RESULTS AND DISCUSSION

Maximum Heat Transfer Due to Shock Impingement on an Unswept Leading Edge

The present shock-impingement investigation was conducted in the Langley Mach 8 variable-density hypersonic tunnel at a free-stream Reynolds number $R_{\infty,D}$ based on the model diameter of 1.8×10^5. The models consisted of a sharp flat plate inclined at an angle of 12° to the test-section flow and a right circular cylinder 1 inch in diameter mounted normal to the test-section flow. The cylinder was constructed of a mica and glass composite material having a low thermal conductivity and, thus, data could be obtained by using the phase-change-coating technique outlined in reference 14. With this method it is possible to obtain the location and peak value of any local increases in heating with better accuracy than can be obtained on conventional thin-skin heat-transfer models.

The tunnel flow was started with the wedge in place and then the cylinder was injected into the wedge flow field. The end of the cylinder was kept far enough from the surface of the wedge so that no flow separation occurred on the wedge surface ahead of the cylinder. To provide reference heat-transfer-coefficient values for an unswept leading edge without shock impingement, the cylinder was also tested without the wedge.

A schlieren photograph and accompanying explanatory sketch of the flow in the vicinity of the leading-edge model is shown in figure 3. From this figure it is evident that no root separation occurred and comparison of this schlieren with the one shown in figure 4 for the cylinder alone indicates that shock impingement occurred far enough from the tip so that the leading-edge flow was almost fully developed before impingement occurred. The general features of the flow field are similar to those shown in figure 2. The vortex sheet which originates at the intersection of the plate shock and cylinder bow shock can be seen in figure 3.

From previous investigations it was expected that a peak in heating would occur in the vicinity of vortex impingement. In the present investigation a peak of this type was measured; however, the magnitude of this peak was only 1.8 times the undisturbed level, corresponding to that on an unswept leading edge without shock impingement, rather than the factors of up to 10 which have been previously measured (ref. 6). A plot of the maximum measured heat transfer due to shock impingement for the present and previous investigations at $\Lambda = 0^{o}$ is given in figure 5. The maximum value has been divided by the "undisturbed" value obtained far from the shock-impingement region where the leading edge is subjected to the free-stream flow. All data have been plotted as a function of the log of p_2/p_1, which is a slightly modified form of the parameter used in reference 7 to correlate their data with those of reference 5. The pressure p_2 was calculated for all data by assuming that the free-stream flow was influenced by the impinging shock and a cylinder bow shock which was assumed parallel to the cylinder. This assumption was made because schlieren data or pressure data were not available for all cases, and therefore, additional shocks due to separation could not be properly accounted for. (Those investigations for which pressure data were available indicated that when separation shocks were present, the actual value of p_2 was as much as 50 percent higher than the value used.) The theoretical curve shown in figure 5 is therefore the approximate increase in heating which would be expected because p_2 is greater than p_1 (flow separation effects were not considered). The circular data points, which include the present $M = 8$ data, are results for the case of negligible root separation and shock impingement occurring after the leading-edge flow was fairly well developed. For these data, only moderate increases in heating above expected levels seem to occur. The actual increases are up to 50 percent above the values predicted by taking into account the nominal increases in pressure. Also, unpublished data obtained at the Langley Research Center seem to agree with these results. These data were obtained at a Mach number of 8 by Davis H. Crawford for an unswept leading edge under similar conditions (that is, no root separation and shock impingement occurring after the attached flow was fairly well developed).

The hatched areas in figure 5 indicate data obtained when some root separation was generally present and shock impingement may have occurred inboard of a region of fully developed leading-edge flow. As stated, if proper account could be taken of additional separation shocks for these data, they would be shifted to the right by varying amounts because the value of p_2 would be increased, but this shift would generally not be sufficiently large to bring these data into the same relative agreement with the theoretical curve as that exhibited by the circular data points. Therefore, there seems to be an additional increase in heating for the data designated by the hatched area above that which is observed when impingement occurs fairly far out on a leading edge, as was the case for the circular data points. An interesting feature of these data is that where actual values of p_2/p_1 are known, h_{max}/h_1 is equal to p_2/p_1, within approximately a 30-percent spread in the data. The reason for this apparent equivalence between the heat transfer and pressure ratios is not known at the present time.

The cross-hatched areas indicate data (reported in ref. 6) obtained when shock impingement occurred in close proximity to a separated-flow region at the root and, therefore, when attached leading-edge flow was just starting to form. For these data, the magnitude of the peak was 10 times the undisturbed level. It is concluded by comparison of the data for the three conditions that the magnitude of the increase in leading-edge heating due to shock impingement depends on the proximity of the impingement to the region in which the attached leading-edge flow begins. (That is, when this flow is just beginning to form, the larger flow gradients that would be present there seem to increase the increment in heating caused by the vortex impingement.) For the usual practical case in which impingement occurs fairly far out on a leading edge, only moderate increases in heating would be indicated according to the present interpretation of the results shown in figure 5.

To further validate the conclusion that h_{max}/h_1 increases as the shock-impingement location approaches the tip or root of the leading edge, additional data were obtained by increasing the distance from the plate to the end of the cylinder. This increased distance caused the shock impingement to occur closer to the end of the cylinder. The results of these tests are shown in figure 6 in which Δ is defined to be the distance from the point at which the leading-edge shock begins to form (for the present tests, the end of the cylinder) to the location of the vortex impingement (fig. 2).

From figure 6 it is evident that the increment in heating due to shock impingement does increase as the tip is approached. This tip effect is probably, at least in part, due to the occurrence of shock impingement closer to the tip where the bow-shock-layer thickness decreases, and therefore the distance from the origin of the vortex sheet to the impingement region on the leading edge is reduced. Hence the distance over which the vortex sheet grows and diffuses into a mixing layer is smaller. As a consequence, the vortex causes larger increases in heating when it impinges on the leading edge because of the larger gradients in velocity and temperature. If such a mechanism is actually the dominant cause of the increases in heating associated with the tip effect noted in the present investigation, large increases might also occur in the region of developed leading-edge flow if a very small leading-edge radius, which results in a very small shock standoff distance, were used. For the data shown in figure 5 the leading-edge radius was always of the same order of magnitude.

The results of a recent investigation of a different but analogous configuration conducted at the Langley Research Center by Robert A. Jones are apparently in agreement with the present conclusions concerning shock impingement. The configuration tested was a forward-facing probe projecting from the windward region of an Apollo command module in the reentry attitude. (The probe has been proposed as a possible reentry communication antenna.) A schlieren photograph of the flow over the configuration is shown in figure 7. From this figure it is seen that the probe tip was ahead of the main-body bow shock and, therefore, impingement of this shock occurred along the lower portion of the probe. The resultant flow within the main-body flow field is almost normal to the probe so that this portion of the probe can be treated as a cylinder at some small effective sweep angle to the local flow. The measured peak in heating occurred just downstream of shock impingement on the lower side of the probe. This measured peak was approximately a factor of 2 above the value calculated for an unswept cylinder exposed to the internal flow near the probe and, hence, is in agreement with the present leading-edge data in which root separation or tip effects were not large.

Effect of Chordwise Grooves on Leading-Edge Heat Transfer

The investigation of leading-edge heating in the presence of chordwise grooves was also conducted in the Langley Mach 8 variable-density hypersonic tunnel over a nominal Reynolds number range $R_{\infty,D}$, based on the 0.75-inch leading-edge diameter, of from 3×10^4 to 3×10^5.

The model tested was a 76° swept slab fin with a semicylindrical leading edge. The fin was mounted on a flat plate 10 inches from the plate leading edge. The fin was constructed of high-temperature plastic and the phase-change-coating technique of reference 14 was also used to obtain heating data on this model. The fin was cast with grooves alined normal to the leading edge and spaced 0.5 inch apart along the entire length of the model. The grooves were square in cross section, 0.030 inch on a side, and extended around to the sides of the fin. The leading edge of the model was 14.4 inches in length.

During the tests a weak shock that gave a 2° turning angle to the approaching flow was observed to originate near the plate leading edge, and this shock altered slightly the effective free-stream conditions for the leading edge. The Reynolds number range quoted for these tests includes this correction.

The measured Nusselt number variation along the fin leading edge at $R_{\infty,D} = 1.74 \times 10^5$ is shown in figure 8. The spanwise locations of the grooves are indicated in the figure. The variation of N_{Nu} with x/D downstream of a given groove is similar to that near the leading edge of a flat plate or near the tip of a cylinder. This variation can be explained by noting that the grooves provide a channel for removal or bleedoff of a portion of the stagnation-region boundary layer because of the large decrease in pressure from the stagnation region to the sides of the fin. Thus, if each groove bleeds off a portion of the leading-edge boundary layer, a new sublayer forms downstream of each groove. The subsequent growth of this sublayer would then result in a heating distribution analogous to that near the sharp tip of a cylinder. Further details concerning this postulated mechanism and results of approximate calculations are available in reference 15. The general level of heating for this value of $R_{\infty,D}$ is not very different from that predicted by the application of swept-cylinder theories (ref. 16) as indicated on the right-hand side of figure 8.

The variations with $R_{\infty,D}$ of the maximum and minimum values of N_{Nu} measured downstream of a typical groove at $x/D \approx 12$ is shown in figure 9. Also shown for reference are the predictions of the theories of reference 16 and leading-edge data obtained on the same model without grooves. The data for the fin with grooves is seen to be below or about the same as the data for the smooth or plain leading edge, depending on the Reynolds number. The gradual increase with $R_{\infty,D}$ of the grooved-fin data is believed to be due to more of the upstream boundary layer being bled off by the groove at higher $R_{\infty,D}$ values and the consequent increase in external velocity for the sublayer downstream of a given groove with increasing Reynolds number. This postulated mechanism is currently under further evaluation at Langley Research Center by the author.

The present results are for a particular groove size, leading-edge diameter, and Reynolds number range. On the basis of the postulated mechanism for the observed increases in heating with increasing Reynolds number (see fig. 9), it can be expected that a larger groove would presumably cause more bleed and, hence, could cause higher heating levels than those measured in the present tests.

Effect of End Contamination on Leading-Edge Heat Transfer

The data for the 76° swept fin with smooth leading edge shown in figure 9 indicate that transition of the leading-edge boundary layer for this configuration occurred at a Reynolds number $R_{\infty,D}$ of from 1.5×10^5 to 2×10^5. To compare this transition Reynolds number with results from other investigations, a survey of the available heat-transfer data for swept leading edges was made. A portion of the results of this survey, the details of which are reported in reference 15, are summarized in figure 10. For configurations having end plates or adjoining surfaces (that is, configurations similar to the fin-plate combination of the present investigation), the value of $(R_{\infty,D})_{transition} \approx 2 \times 10^5$ adequately (within 30 percent) represents the available data for $\Lambda > 40^\circ$ and $2.5 \leq M_\infty \leq 8$. This Mach number limitation is imposed because transitional or turbulent leading-edge data evidently have not yet been obtained at Mach numbers higher than 8.

For the "delta wing" leading-edge models for which possible end contamination from an adjoining surface would not be present, most of the available data with the exception of two or three cases indicate that for Reynolds numbers up to 8×10^5 the leading-edge flow remains laminar. A Reynolds number of 8×10^5 is evidently the highest Reynolds number for which leading-edge data on these configurations are currently available.

It can be concluded that some type of end contamination of the leading-edge boundary layer, evidently emanating from the boundary layer of the adjoining surface, causes premature transition of the leading-edge boundary layer at $R_{\infty,D} \approx 2 \times 10^5$ for $\Lambda > 40^\circ$.

CONCLUSIONS

An investigation was conducted to determine the effect on leading-edge heat transfer of shock impingement, chordwise grooves, and end contamination of the leading-edge boundary layer from an adjoining surface. The tests were conducted at a Mach number of 8. The following can be concluded:

1. The present results and comparisons with results of other investigations indicate that the magnitude of the increase in leading-edge heat transfer due to shock impingement for small sweep angles is a function of the proximity of the shock impingement to the tip or root region in which attached leading-edge flow begins. In the usual practical situation impingement would generally occur fairly far out on a leading edge and for this case the present results indicate that only moderate increases in heating of the order of 50 percent over the level predicted by simple theory can be expected.

2. A large number of small chordwise grooves in the leading edge of a 76° swept fin resulted in a heat-transfer distribution downstream of each groove that was similar to the type of distribution which occurs near the leading edge of a flat plate or in a region of developing flow near the tip of a swept cylinder. This distribution was repeated for each groove and was probably caused by removal or bleedoff of a portion of the stagnation-region boundary layer by the grooves. For the Reynolds number range and groove size of the present tests, the general level of heating along the leading edge with grooves was similar to or below that obtained on the same configuration without the grooves.

3. The results of the present tests and a survey of the available heat-transfer data for swept leading edges indicate that for leading edges having an adjoining surface such as an end plate, transition of the leading-edge boundary layer occurs at a free-stream Reynolds number, based on leading-edge diameter, of approximately 2×10^{5} for sweep angles greater than 40° and Mach numbers up to 8. This premature transition is evidently caused by end contamination of the leading-edge flow associated with the presence of the adjoining surface because leading-edge transition has not been generally observed up to Reynolds numbers of 8×10^{5} on "delta wing" configurations where this type of adjoining surface is absent.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 17, 1967,
126-13-03-31-23.

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INTERFERING FLOW FIELDS

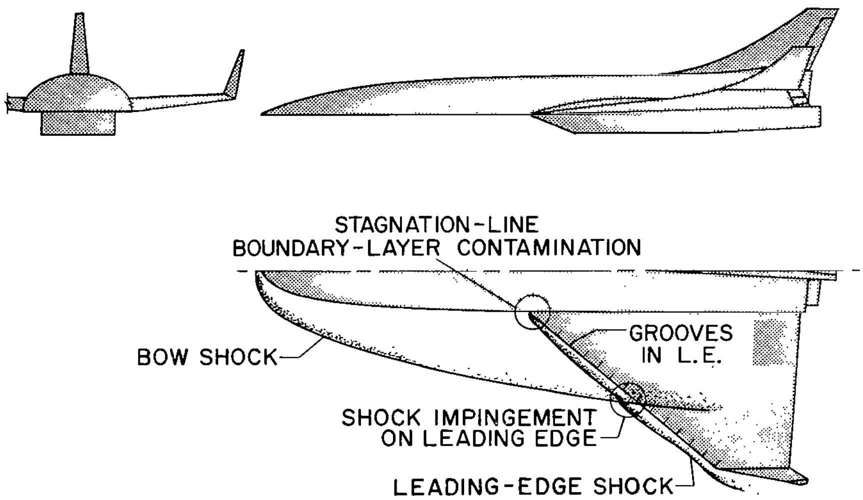

Figure 1

FLOW FIELD
ASSOCIATED WITH LEADING-EDGE SHOCK IMPINGEMENT

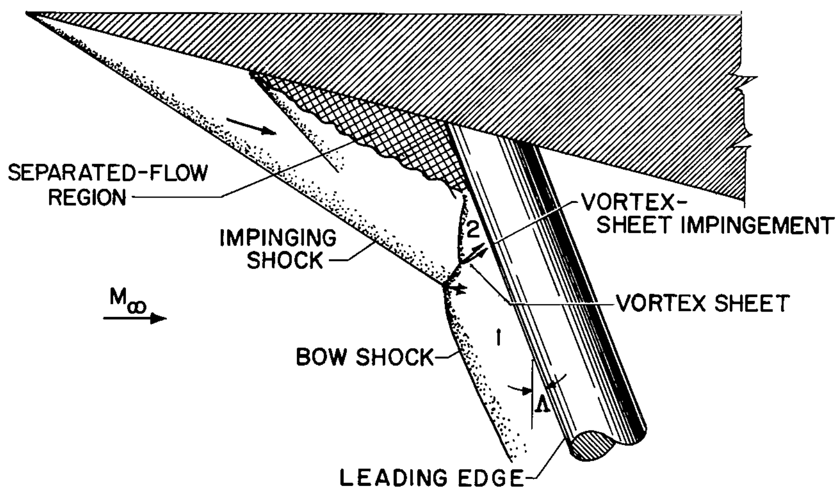

Figure 2

LEADING-EDGE SHOCK IMPINGEMENT

$\Lambda = 0°$; $M_{\infty} = 8$

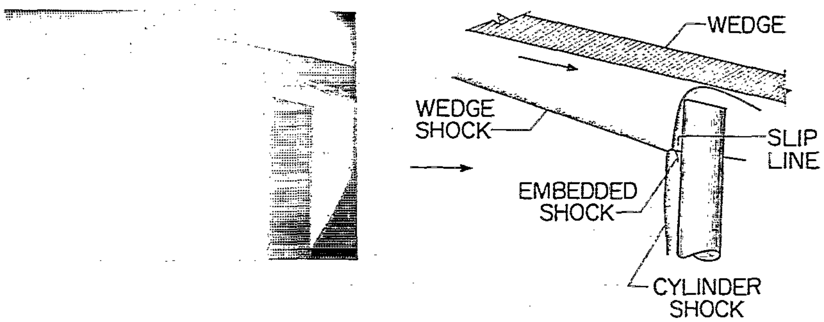

Figure 3

SCHLIEREN OF FLOW OVER UNSWEPT CYLINDER

$M_{\infty}=8$

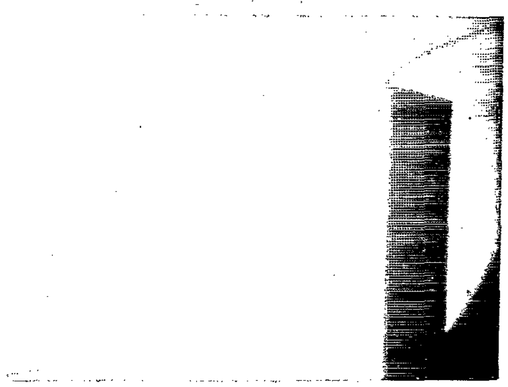

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Figure 4

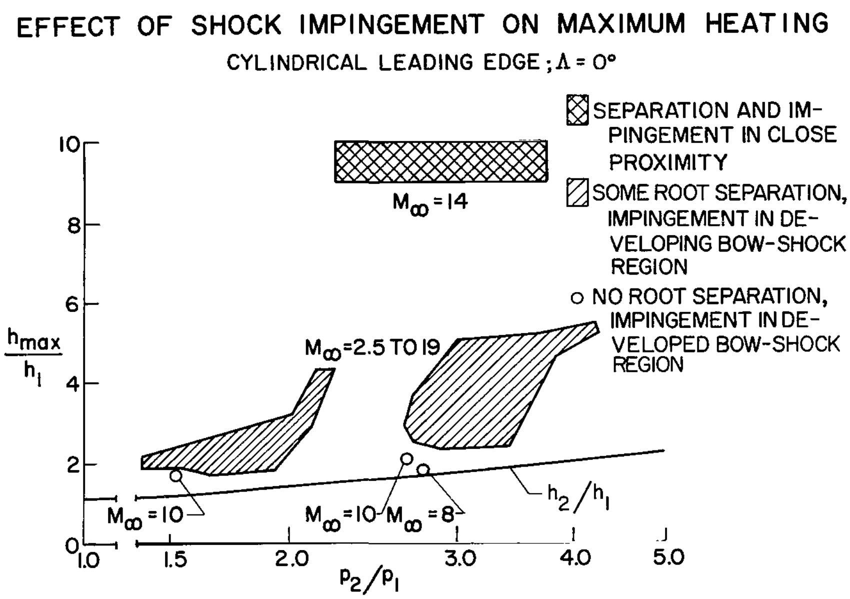

Figure 5

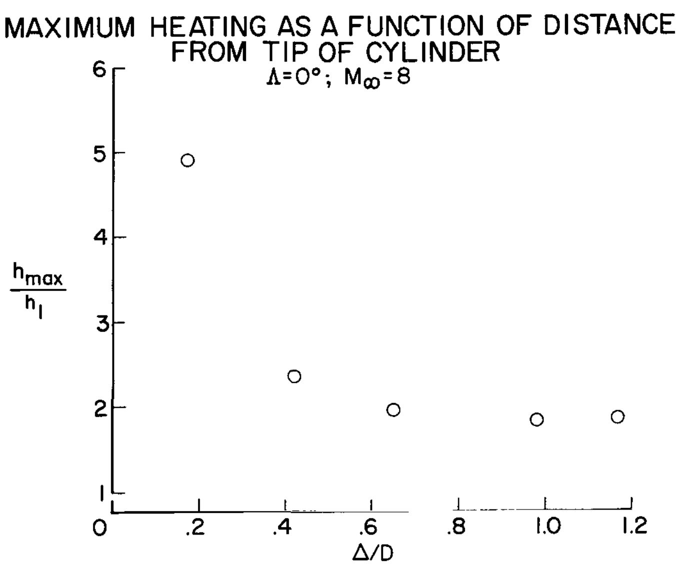

Figure 6

SCHLIEREN OF FLOW OVER APOLLO MODEL
FORWARD-PROJECTING ANTENNA; $M_{\infty}=8$; $\alpha=25°$

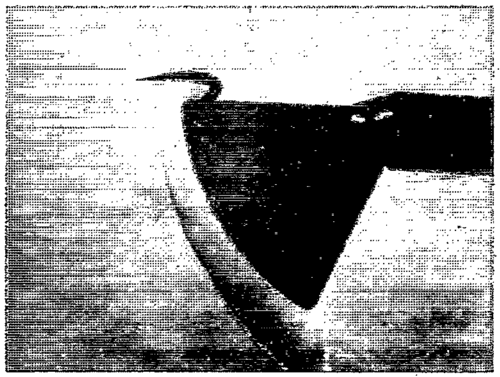

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Figure 7

STAGNATION-LINE HEAT TRANSFER TO GROOVED LEADING EDGE
$R_{\infty,D} = 1.74 \times 10^5$; $M_{\infty} = 8$

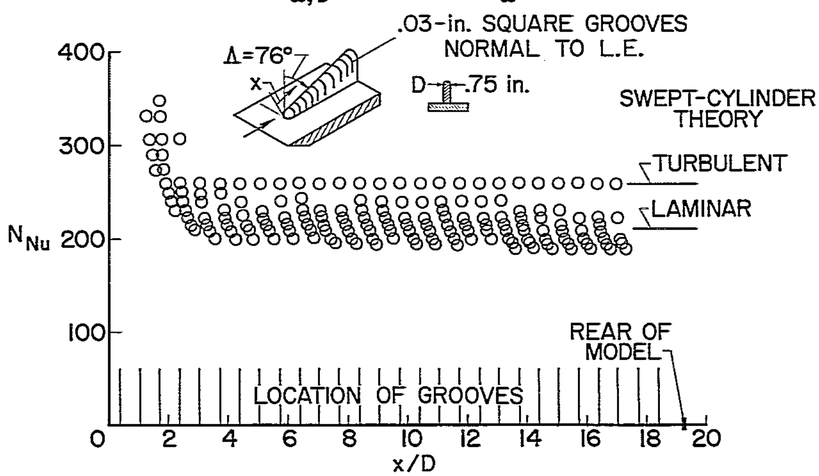

Figure 8

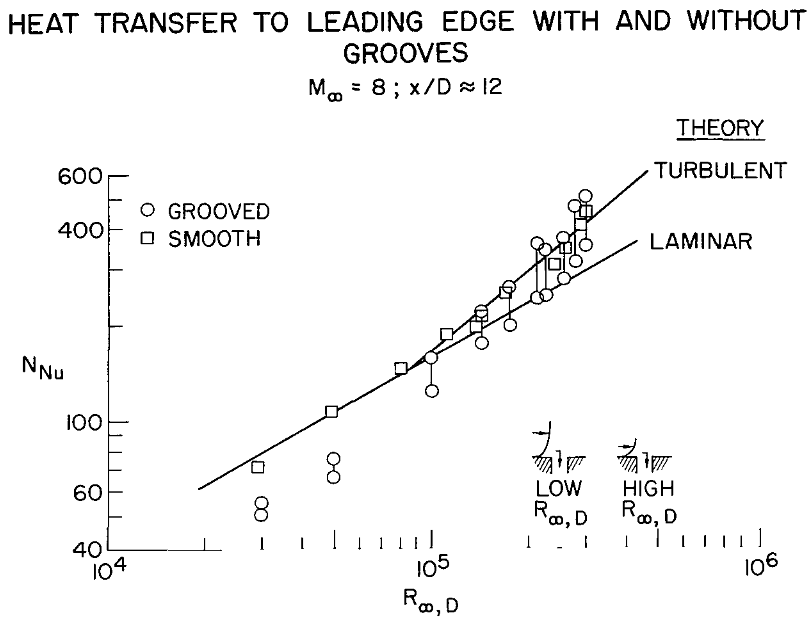

Figure 9

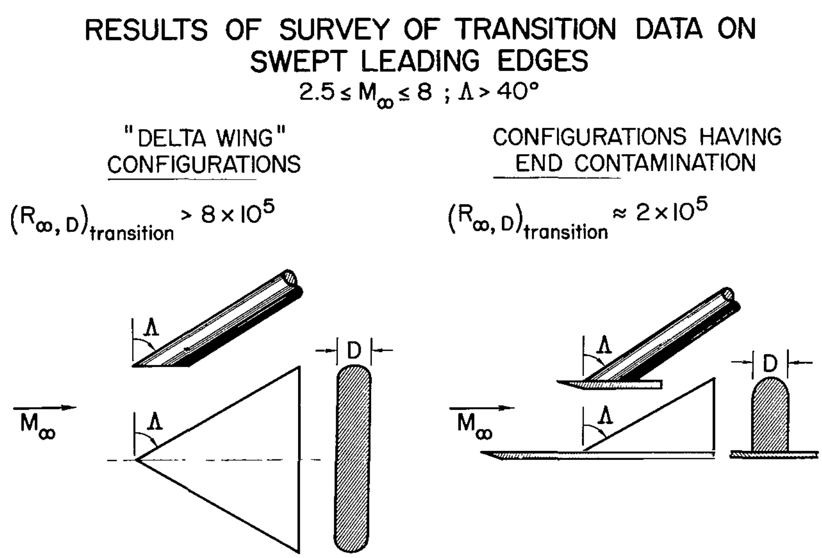

Figure 10

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